10 Mar 1991, 1:00 pm - 3:00 pm

Two Sequences of Fine Grained Soil Liquefaction at Soda Lake, Pajaro River Valley, Santa Cruz County, California

J. David Rogers
Missouri University of Science and Technology, rogersda@mst.edu

C. J. Wills
USA

M. W. Manson
USA

Proceedings: Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, March 11-15, 1991 St. Louis, Missouri, Paper No. LP33

Two Sequences of Fine Grained Soil Liquefaction at Soda Lake, Pajaro River Valley, Santa Cruz County, California

J. David Rogers, C. J. Wills, and M. W. Manson
USA

ABSTRACT

Soda Lake was originally a natural lake in an abandoned meander bend of the Pajaro River. The San Andreas Fault zone lies 350 meters southwest of the lake, on a northwesterly trend. The natural lake was diked with embankments approximately 3 to 6 meters high on its southern and eastern sides in 1968 for use as a tailings pond. Fine waste material from Granite Rock Company's Wilson quarry, located just across the river and approximately 0.5 kilometers west of the lake, was periodically slurried by pipeline over to Soda Lake and thence hydraulically deposited from 1968 to the present.

During the October 17, 1989 M 7.1 Loma Prieta earthquake, the 28 ha (66 acre) floor of Soda Lake settled 0.2 to 1.7 meters with extensive liquefaction boils grouped to its northwestern (high) side. The Loma Prieta epicenter lay approximately 32 km northwest of the site.

On April 18, 1990 a series of aftershocks occurred near Chittenden and was widely felt throughout the Bay Area. The largest of these was a M 5.4 event, within 5 km of Soda Lake. Subsequent examination of Soda Lake again showed extensive liquefaction, with many boils occurring in the same areas as those viewed the previous October. Settlement caused by dynamically induced consolidation of the lake sediments also was observed, with areas of differential settlement bounded by en-echelon tension cracks. In this manner, many of the October 1989 sand boils were neatly truncated by extension cracks formed in April 1990, with 1 to 6 cm displacement. In addition, several boils were observed to be surrounded by mud drops and spattering, suggestive of violent eruption. One boil was observed to be noticeably venting gas three days after the Chittenden swarm. Cross sectional excavations and material samples were taken for grain size analyses and SEM photomicrographs. An average of 87% of the liquefied materials were of minus 200 mesh size (less that 0.074 mm diameter). Scanning electron micrographics shows the grains to be very small, angular and of fairly uniform grain sizes, which is consistent with the manufactured origins of the sediment.

The Soda Lake observations raise interesting questions regarding liquefaction thresholds, grain size criterion, effects of densification on subsequent liquefaction and saturation considerations. Liquefaction was limited to the "drier" (higher) side of the lake, while the older, ponded side did not appear to liquefy. SPT and CPT exploration programs are planned in the hope that such reference data will help to evaluate the credibility of currently-employed liquefaction models.

GEOLOGIC SETTING

Soda Lake is an enlarged remnant of a natural lake sitting on an elevated, abandoned meander of the old Pajaro River, approximately 1 mile upstream of the Pajaro Gap (Figures 1, 2, & 3). The Pajaro Gap is a notch cut into the resistant Mesozoic-age quartz hornblende diorite that forms the southwestern side of the San Andreas fault in this area. It represents the only water gap south of the Golden Gate between the inland Santa Clara-San Benito trough and the sea (Allen, 1946).

Bedrock units in the Soda Lake area are quite different on either side of the San Andreas fault (Figure 4). Northeast of the fault the units are dominantly fine-grained marine sedimentary rocks of Tertiary age. Southwest of the fault, bedrock consists of Mesozoic

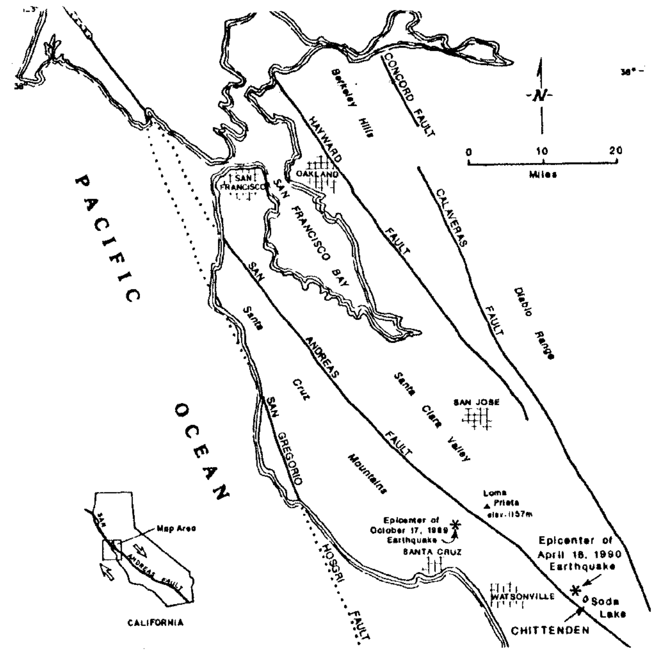

Figure 1 - *Map of the San Francisco Bay area showing faults that make up the San Andreas fault system and epicenters of the Loma Prieta and Chittenden earthquakes. From Wills and Manson (1990).*

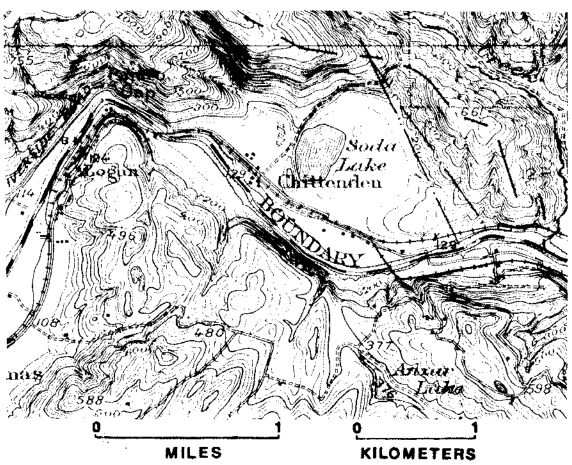

Figure 2 - *The 1917 U.S. Geologic Survey topographic map of the Soda Lake area (scale 1:24,000) which shows the outline of "natural" Soda Lake.*

hornblende quartz-diorite overlain by Quaternary and Tertiary eolian sand, and both mariné and non-marine sand and gravel. These units have been fractured or folded or both, and locally have been cut off and displaced by fault movement. Soda Lake appears to be fed by natural springs and, according to Allen (1946), an "oil spring" verging from a splay of the San Andreas fault, which likely cuts across the north end of the lake. (Figure 4).

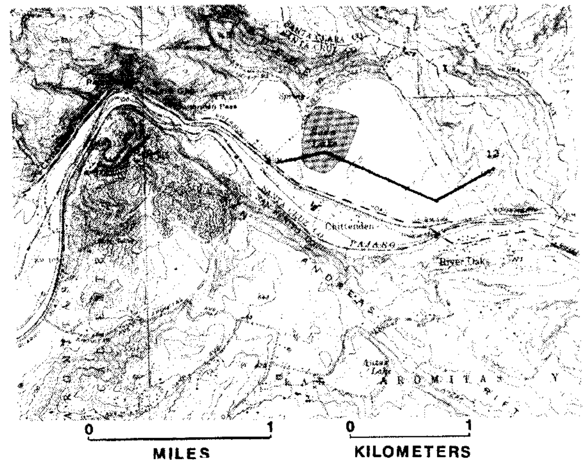

Figure 3 - *The 1980 photo-revised topographic map of this area which shows artificially enlarged Soda Lake and its perimeter dikes. The location of the cross section in Figure 5 is shown by heavy line.*

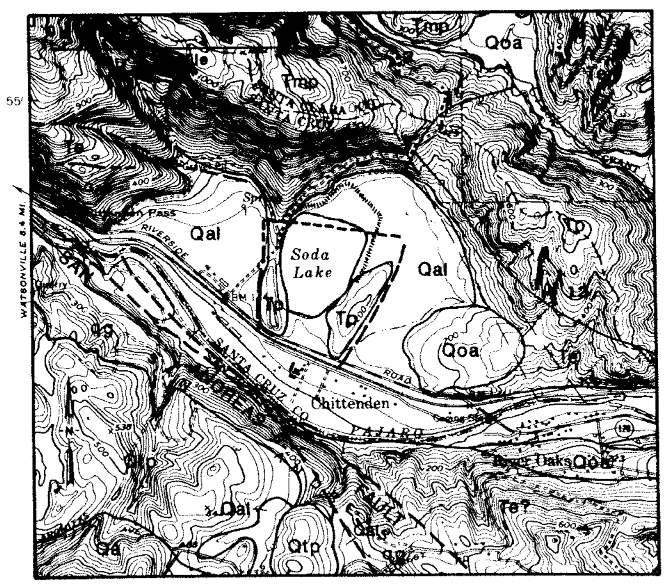

Figure 4 - *Geologic map of the Soda Lake area (from Dibblee and Brabb, 1978) with traces of active faults (by Bryant and others, 1981).*

Jenkins (1973) postulated that the "Pajaro notch" had originally been excavated by the ancient San Benito river system some 11.3 kilometers to the southeast, from whence it has been carried northwestward by the San Andreas over the past 320,000 years (at an assumed slip rate of 3.5 cm per year). Jenkins (1973) went on to propose that seismically-induced landslides accompanying the northwestward-translation of the granite ridge and its contained gap into the higher Anzar Hills truncated

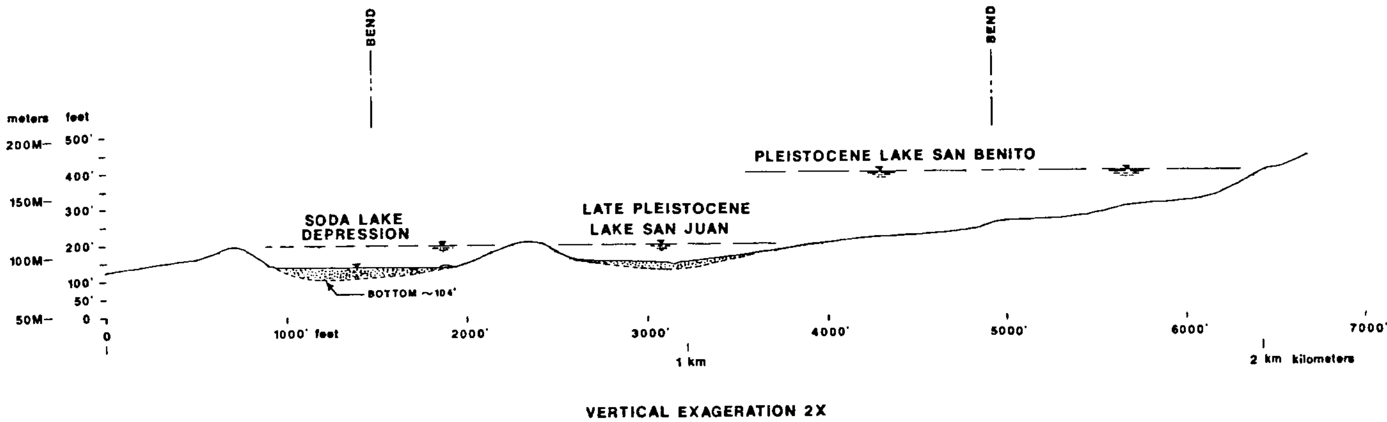

Figure 5 - *Cross-section of the Soda Lake basin with elevations of Pleistocene Lakes San Benito and San Juan. Depth to bedrock in Soda Lake is based on channel gradient.*

the river system outlet, thereby creating Pleistocene Lake San Benito at an elevation of approximately 122 meters (400'), sometime in the last 100,000 to 200,000 years (Figure 5). Pleistocene Lake San Benito appears to have occupied a basin 48 km long and approximately 16 km wide. Jenkins proposed that it persisted for at least 50,000 years based on the breath of its terraces and distinctive lacustrine deposits, the most marked of which is a blue clay facies deposited unconformably upon alluvial gravels and ancient channel cobbles in the Hollister area (Ellis, 1952). The widespread occurrence of a 122 meter high terrace in this basin suggests that Lake San Benito must have had some semi-stable outlet, possibly north of Morgan Hill into the Coyote Creek drainage, and thence into the San Francisco Bay depression. In previous eras, the Coyote Creek may have flowed south, into Lake San Benito.

Sometime late in the Pleistocene, Lake San Benito excavated an outlet to the sea across the San Andreas fault and drained itself down to an elevation of around 61 m, a stage Jenkins (1973) called Lake San Juan (Figure 5). It was during the Lake San Juan stage that river terraces at the 61 m level were apparently formed in the area of Soda Lake, just upstream of the current Pajaro Gap. The meandering nature of the ancient Pajaro channel is evident from the abandoned cul-de-sacs so vividly seen in the present-day topography in the vicinity of Soda Lake (Figures 2 and 3). Channel meanders are generally indicative of flowage on a low hydraulic gradient with large quantities of suspended sediment on a relatively soft river bed. The low gradient was likely controlled by slow excavation of the hard granite ridge at the San Andreas fault and by the high sediment loads, a consequence of re-entrenchment through the soft San Benito and San Juan lake sediments.

BREAKOUT OF LAKE SAN JUAN

If we believe Jenkins' offset channel hypothesis, sometime in the late Wisconsin time the "Pajaro Notch", previously cut into the diorite, was faulted to a position opposite Soda Lake and the elevated waters of Lake San Juan quickly broke through the notch, thereby draining ancient Lake San Juan. Jenkins (1973) summarized a great deal of evidence for this breakout, in the forms of the temporary lakes and multiple spillways which were created downstream, mostly in the Aromas area, until the modern Pajaro channel stabilized its gradient.

Prior to 1968, Soda Lake's water surface lay at an elevation of approximately 41 meters. The ancient channel gradient was likely close to the present day slope (0.30 % slope) or somewhat less (as would be expected with a greater quantity of water during the late Pleistocene). The new Pajaro Channel likely pierced or aligned with the displaced Pajaro (Gap) Channel in the diorite when the gap was translated to within 2000 m of its current position, which at a slip rate of 3.5 cm/yr would have occurred around 60,000 year ago (Figure 6A). The Soda Lake Channel likely formed much later, after the Gap began to be pinched off some 20,000+ years ago (Figure 6B). The flow through the gap at the time of the "Soda Lake Channel" (in which Soda Lake now sits) would likely have been between 33.5 m and 39.6 m (for flow distances of 2.4 km and 0.80 km downstream of Soda Lake, respectively). This sequence of breakthrough through the Pajaro Gap and subsequent right-lateral offset of the gap is sketched diagramatically in Figures 6A, 6B and 6C.

As the buried granite channel was displaced northwestward, it eventually came into a position coincident with the Lake San Juan spillway channel, which must have made short work of its re-excavation, thereby precipitating a breakout of the lake. Breakouts of entrained lakes through landslide dams or similar, unconsolidated materials commonly occur as short-lived catastrophic events, whereupon rapid channel incision and realignment can be accomplished in a matter of a few hours or days. Ancillary effects of such rapid water level adjustment as lake draining would be widespread landsliding, commonly associated with rapid drawn-down pore pressure conditions in the lake's saturated side slopes. Additionally, sliding in the Pajaro Gap area could have been precipitated by sudden oversteepening of channel-side slopes and/or seismically-induced slope failures.

After the breakout, channel gradients in the Pajaro Gap area could be expected to be oversteepened in a series of rapids, until sufficient flowage had occurred to move the entrapped sediment through the system. Such rapids may have persisted in the gap area for thousands of years. The longitudinal gradient of the Pajaro River shows that the river still exhibits an increased gradient through the Pajaro Gap, being somewhat less up and downstream of this area. The rapid downcutting of the Pajaro channel truncated the meanders containing Soda Lake and a smaller unnamed depression just to the west leaving them as terraces. Subsequent right lateral offset of the Pajaro Gap requires an increasingly lower channel, thereby serving to "elevate" the Soda Lake depression.

Displacement of the Pajaro Gap over the past 20,000+ years has likely lead to periodic interruption of the Pajaro River discharge. "Pinching-off" with the Pajaro Gap could also be expected to cause periodic ponding of the River until sufficient discharge is stored to re-excavate the channel through overtopping. Over the past 20,000+ years, the necessary re-excavation has been along the active trace of the San Andreas fault, as the channel attempts to keep pace with the offset bedrock Gap. A hydraulic choke is created at the incision point, which would necessitate an increased channel gradient (rapids) so that excavation of the resistant diorite could occur. Upstream and downstream of this perturbation one would expect to see a diminished, low-energy gradient, as the stream conserves its energy for downcutting at the rapids (Leopold and others, 1964). A meandering channel would be a likely result of a low-energy gradient, and this is manifested in the series of meander scars above the Gap (Figure 6B). After the river re-establishes its channel, the channel readjusts its overall gradient to return to equilibrium. The last adjustment served to shorten the main channel, above the Gap, and abandon the meander channels on an elevated shelf. From the cross section in Figure 5, it can be seen that the Soda Lake depression is an old meander channel filled with sediments to a probable depth of some 9+ meters.

STABILITY OF THE SODA LAKE DEPRESSION

The Soda Lake depression is flanked by numerous ancient landslides and active accumulation of colluvium, emanating mainly from the 122 meter level Lake San Benito terraces. It is likely that the abandoned meander was gradually filled by colluvial accumulation. Jenkins (1973) has suggested that landsliding occurred off of the adjacent Lake San Juan terraces, which effectively blocked discharge to the incising Pajaro channel. We can assume that insufficient watershed, and thereby, stream power, exists to re-excavate an outlet to the Pajaro River. This inability to cut an outlet is likely exacerbated by the pervious nature of the underlying Soda Lake bed that appear to soak up ponded water in lieu of storing it sufficiently to precipitate overtopping.

We are left to conclude, therefore; that Soda Lake has persisted as a natural lake through the Holocene for the following reasons:

(1) It possesses sufficient natural storage area to retain both natural runoff and spring-fed waters without overtopping.

(2) Its underlying bed likely consist of moderately permeable channel deposits capable of absorbing large amounts of runoff.

(3) It does not receive sufficient natural sediment to fill its basin.

(4) It is consistently fed by natural springs, possibly caused by perching of near surface groundwater

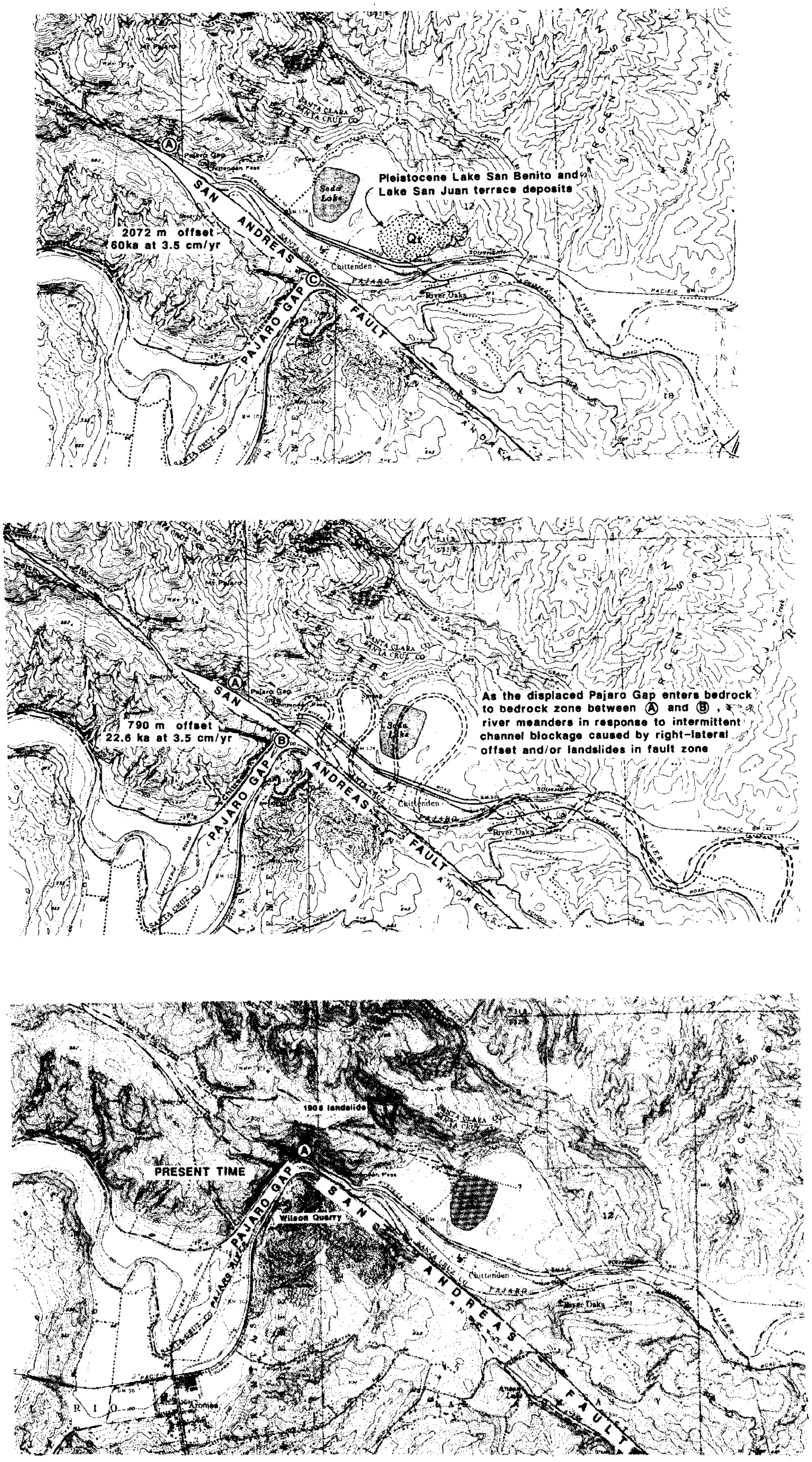

Figure 6 - *Geomorphic evolution of the Soda Lake basin as the pre-existing Pajaro Gap was translated past Soda Lake along the San Andreas fault;*

A) 60 ka at the time of the initial breakout of Lake San Juan,

B) 22 ka, showing the meandering course of Pajaro River that formed the Soda Lake Basin,

C) Present configuration, with a straightened Pajaro River and present-day Soda Lake in an abandoned meander.

along the projection of a well-recognized splay of the San Andreas Fault. It is seldom a perennial lake; therefore, vegetation has not had much opportunity to grow in the basin and fill it in.

(5) Soda Lake has never stored sufficient water to cause the overtopping of its margin long enough to excavate a permanent outlet channel (although older outlets could have been subsequently closed due to sliding, erosion infilling, or seismically-induced ground movements).

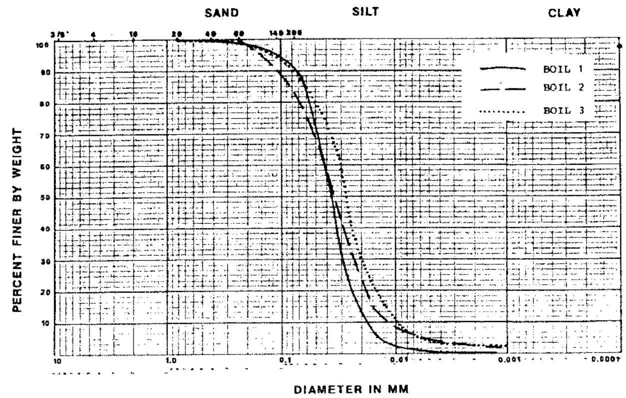

Figure 7 - *Standard Graduation curves for three samples from liquefaction boils at Soda Lake.*

WILSON QUARRY OPERATIONS AT SODA LAKE

Prior to 1900, rock began to be quarried from the resistant quartz hornblende diorite comprising the massive ridge on the southeast side of the Pajaro River, just south of Pajaro Gap. Granite Rock Company took over the property in 1895, and has operated it continuously since (Higgins, 1989). In 1968 Granite Rock Co. constructed dikes around the north, south and east sides of Soda Lake, thereby increasing its holding capacity some three-fold (Figure 3). Minus sand size rock flour, or "fines", produced by the quarry's crushing operations and tectonic movement of the San Andreas fault were caught by aggregate washing and periodically slurried the 1 kilometer distance down across the Pajaro River and into the northwestern corner of the newly-enlarged Soda Lake basin.

The last period of sluicing prior to the Loma Prieta earthquake was in the mid-1980's. Because the pipeline outfall is in the northwest corner of the diked basin, some natural hydraulic and gravimetric sorting of grain sizes could be expected as the slurries were decanted across the lake bottom.

Standard Graduation curves for three of the rock flour/fines mixtures taken from Soda Lake are presented in Figure 7. These mixtures average 87% passing the No. 200 sieve, but large enough to classify all of the mixtures as silt. Photomicrographs of one of these samples are presented in Figures 8. Note the extremely angular nature of the crushed rock, regardless of the individual grain sizes.

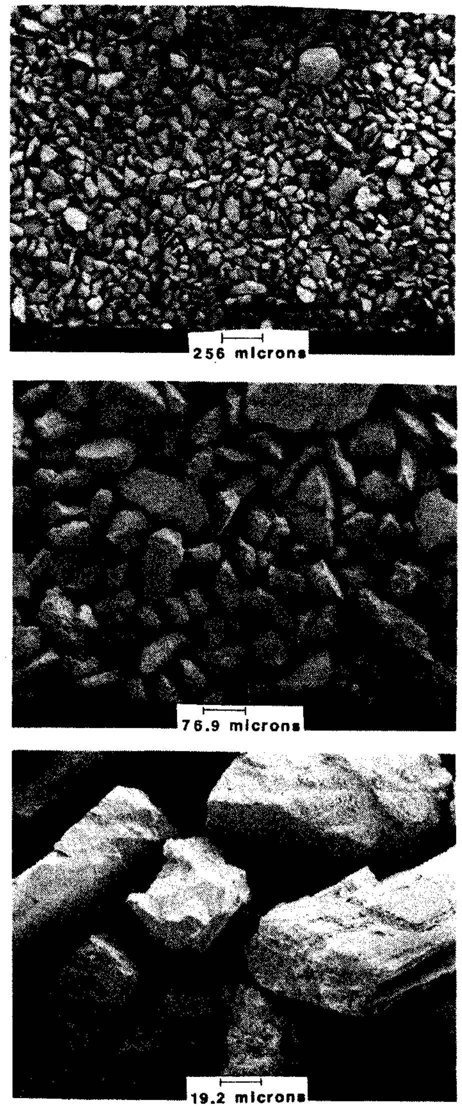

Figure 8 - *Scanning Electron photomicrographs of silt grains that erupted from a liquefaction boil on 4/18/90 at Soda Lake.* Photo taken at the U.C. Davis facility for Advanced Instrumentation

RECENT SEISMIC EVENTS

A number of sizable earthquakes have been recorded in the greater Pajaro Gap/Soda lake area. These include

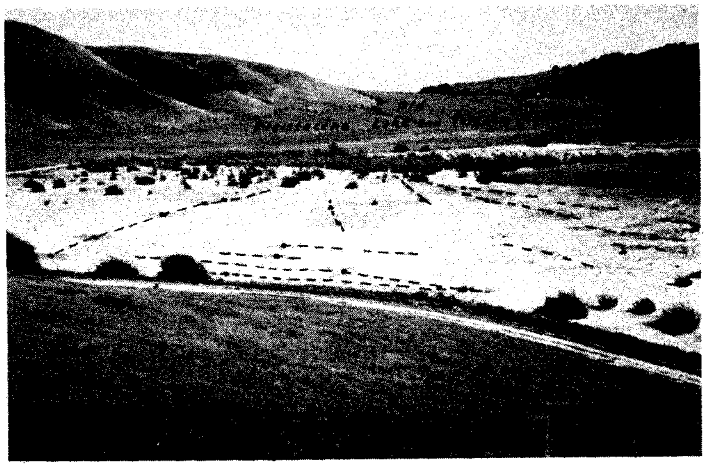

Figure 9 - *Overview of Soda Lake from the west, showing alignment of fissures and liquefaction boils. All photographs by Rogers/Pacific, Inc.*

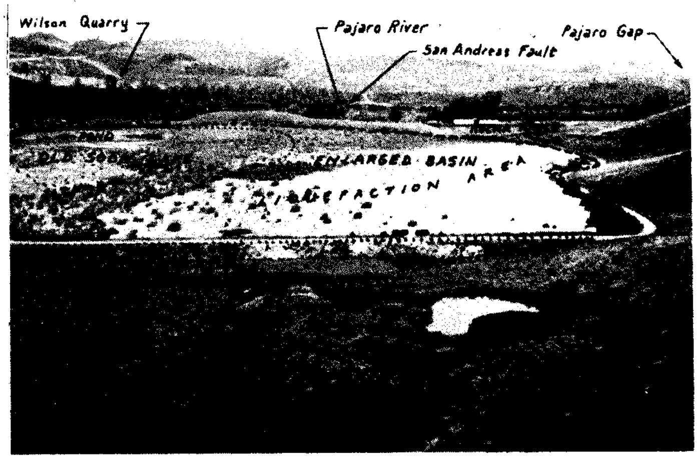

Figure 10 - *Overview of Soda Lake from the north showing area of extensive liquefaction of recent hydraulically deposited silt.*

the M 7.0 San Francisco quake of June, 1838 (Louderback, 1947), the M 6.3 Santa Cruz Mountains quake of October, 1865 (described in Huber, 1929), the M 8.3 San Francisco quake of April, 1906 (Jordan, et al, 1907; Lawson, 1908) the Lake Elsman events of 1988 and 1989 (M 5.1 and 5.2), the M 7.1 Loma Prieta event of Oct. 1989 and the M 5.4 Chittenden swarm of April 1990.

There are no reports of liquefaction in Soda Lake caused by the April 18, 1906 San Francisco earthquake, which was centered some 130 km to the north, opposite the Golden Gate (Bolt, 1988). Severe ground shaking within the Pajaro Gap area was documented (Lawson, et al 1908, Youd and Hoose, 1978). At Chittenden, several buildings were shifted off their foundations and the west abutment of the Southern Pacific Railroad Bridge over the Pajaro River, built directly upon the surface trace of the San Andreas fault (1100 meters west of Soda Lake), was shifted 1 meter north of its previous position (see Derleth in Jordan, et al 1907). A large landslide was triggered at the mouth of a canyon just west of Soda Lake, along a splay of the San Andreas fault (Figure 4). In addition, severe liquefaction and fissuring occurred along the Pajaro River and Salinas River. As the 1905-06 winter was the wettest in 10 years, Soda Lake was probably full of water during the 1906 earthquake.

LOMA PRIETA EARTHQUAKE

At 5:04 p.m. Pacific Daylight time on October 17, 1989, the M 7.1 Loma Prieta earthquake shook the Santa Cruz Mountains area with an epicenter approximately 30 km northwest of Soda Lake (Figure 1). The quake rupture was bimodal (spreading in both directions from its origin) and basal rupture was very short, only 6 seconds. Maximum site responses of up to 15 seconds were recorded at various sites. Vertical acceleration components were quite severe in the Southern Santa Cruz Mountains and nearby coastal plain (up to 0.27g at the nearby Highway 101/156 overcrossing, 5.6 kilometers southeast of Soda Lake). Liquefaction occurred in many of the expected places during and shortly after the quake and caused damage in San Francisco and around the margins of San Francisco Bay. Extensive liquefaction occurred along Monterey Bay, the Salinas River and the Pajaro River and caused severe damage.

The Loma Prieta event caused an extensive series of sand boils to erupt from the largely dry bed of Soda lake. The sandy-silt boil deposits were as large as 3 meters in diameter by 0.30 meters high. Water continued to flow from several sand boils 4 days after the main shock (there were a number of moderately-sized aftershocks during that same period, ranging from M 4 up to M 5.4). Sand boils tended to be clustered along arcuate fissures, some of which paralleled the edge of the diked basin. These relationships are shown in Figures 9 and 10.

The relatively high vertical accelerations (0.25 to 0.35g) from the Loma Prieta quake also caused the northern half of the lake bed to subside 0.60 to 1.5 meters, as shown in Figure 11. The fissured zone along the edge of the lake was very sharp in some locales (such as that depicted in Figure 11) and more gradual in others, where it was distributed in stepped tension scarps across a 15 to 30 meter-wide zone, adjacent to the basin's edge.

THE CHITTENDEN SWARM

On the morning of Wednesday, April 18, 1990, the anniversary of the great 1906 San Francisco earthquake and in the middle of California's annual *Earthquake Awareness Month*, a series of aftershocks of the October, 1989 Loma Prieta earthquake occurred near Chittenden, close to Soda Lake and at the southern end of the Loma Prieta rupture. The largest of these was a M5.4 event that occurred at 6:54 a.m. local time, epicentered about 5 km northwest of Soda Lake. Extensive liquefaction again occurred at Soda Lake as a result of the Chittenden swarm. The northern half of the 28 ha (66 acre) lakebed was covered by fissures and sand boils, such as the one shown in Figure 12.

As was the case 6 months earlier, boils tended to be aligned along broad arcuate tensile fissures, through which the boils welled up and excess water was observed to flow two days after the quake. The linear nature of the boils is shown in Figure 13. In some instances, the older Loma Prieta tension cracks were re-opened, but insufficient amounts of sand were expelled to fill many of the cracks completely, as shown in Figure 14. Only minor collapse and settlement of the lakebed was observed after the smaller Chittenden quakes. Some of the observed patterns were very interesting, however, in Figure 15, 2 to 8 cm of lakebed settlement was noted along several of the tensile fissures from the previous Loma Prieta event. The dropped side of such fissures was consistently directed towards the south, in the direction of the natural lakebed. Expelled water also flowed towards the south (which is also the lower, more saturated side of the lake). In Figure 16, a series of concentric fissures surrounding a series of boils is suggestive of localized collapse, presumably associated with volumetric changes. Note how expelled water flowed back into these arcuate cracks.

In several instances the boil eruptions appear to have been rather explosive, sending out mud spatters and fluidized clay. Another boil was observed to be venting

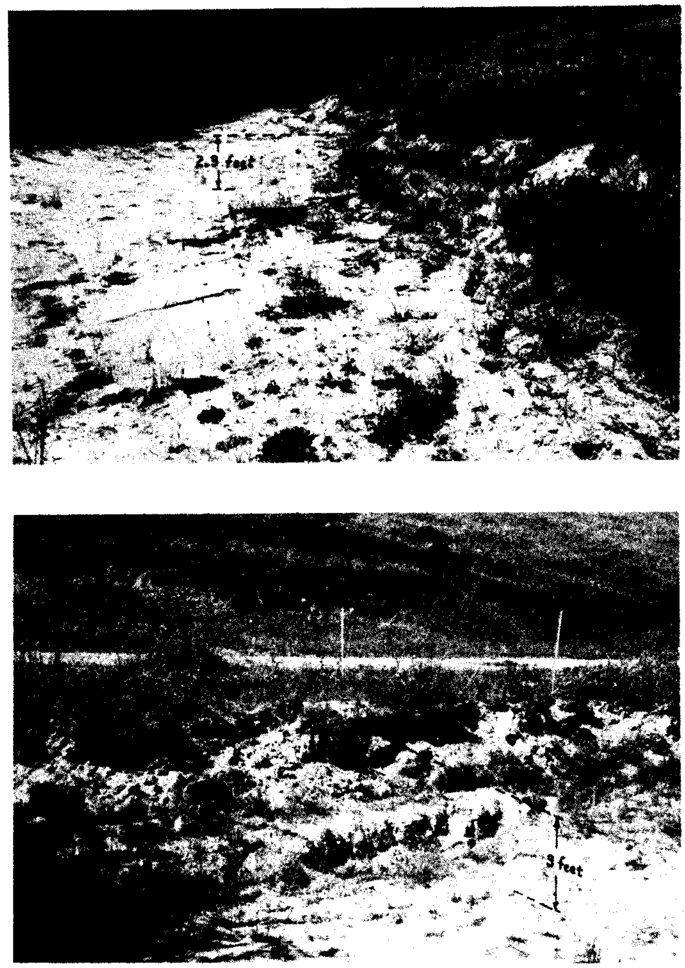

Figure 11 - *Settlement scarps along the edge of Soda Lake (A and B).*

Figure 12 - *Typical liquefaction boil at Soda Lake, April 18, 1990.*

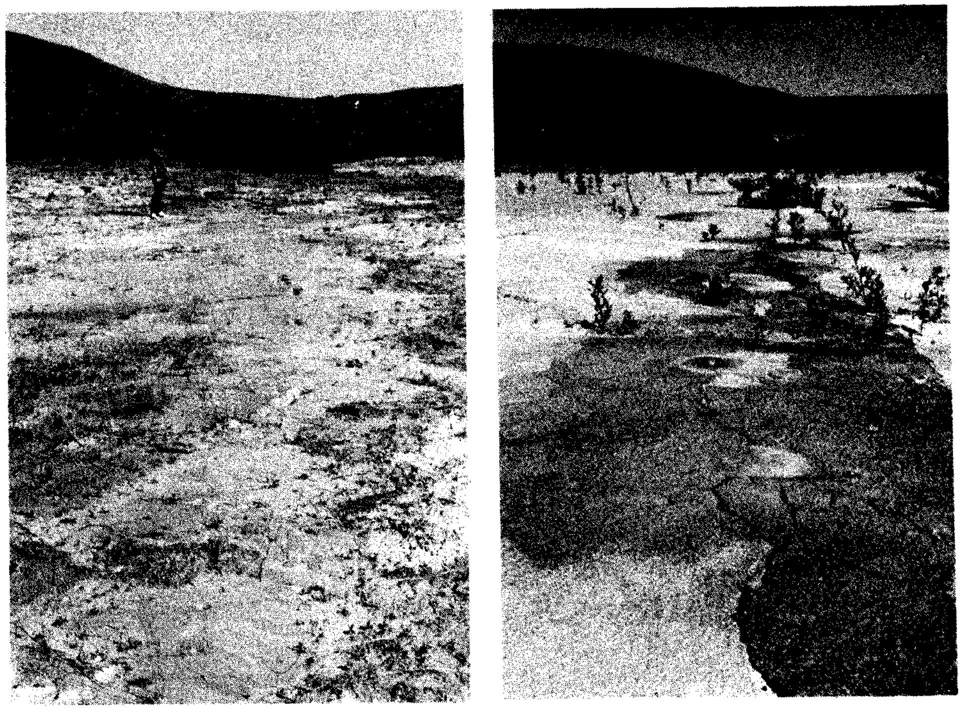

Figure 13 - *Aligned liquefaction boils at Soda Lake.*

noticeable amounts of natural gas (presumably methane) some 56 hours after the quakes. The source of this gas might be shallow decaying organic matter or the "oil spring" noted previously in this area by Allen (1946).

One of the new boils was hand excavated to a depth of 0.61 meters two days following the Chittenden swarm. This excavation is shown in Figure 17. The excavation showed 20 cm of moist, recently expelled olive-colored silt overlying what appeared to be much drier tan-colored sandy silts, presumably comprising the pre-Loma Prieta basin surface. Two distinctively-colored dikes, 1 to 2 cm wide, were observed to be cutting across the tan colored silts; one feeding the recent, observed boil, and the other petering out in the overlying, liquefied silt.

Other portions of the Soda Lake basin did not appear to exhibit liquefaction. In part, this may be because those areas were either more dry or underwater (Figure 18), or because the southern 2/3 of the basin have only a thin veneer of tailings underlain by the older, natural sediments comprising old Soda Lake (Figure 10 and comparison of Figure 2 with Figure 3). We can presume that the natural Soda Lake sediments are sufficiently aged to have been previously subjected to many seismic loadings, and through such loadings, have achieved sufficient relative density so as to resist liquefaction within the relatively short shaking durations experienced in either event. An alternative hypothesis is that these older sediments are more cohesive, and therein, less prone to liquefaction.

Indeed, the large degree of dynamically-induced settlement noted along the northern margins of the basin suggests that much or most of the material which densified was post-1968 slurried rock flour/silt, hydraulically deposited by Granite Rock Company. Lower-than-normal winter precipitation and lack of use by the quarry over the previous 4 years lowered the ground water level in the basin. Such draw down would be sufficient to increase effective unit stress in the tailings on the northern, high side of the basin (the soils would feel less effective stress when saturated, due to buoyancy). The extreme southern portion of Soda Lake was saturated with 0.1 to 0.6 meters of standing water during the Chittenden events. No evidence of liquefaction was observed in this area.

However, volumetric displacements due to the rapid expulsion of pore water and boiled silt cannot begin to account for the observed settlements (0.6 to 1.6 meters). It has long been recognized that hydraulically-emplaced sands may possess low relative densities and high initial void ratios (Seed and Makdisi, 1977). Fine-grained sand, hydraulically-deposited in a laboratory flume has been shown to possess initial void ratios in excess of 1.0 (Rogers, 1982). Gilboy (1933) demonstrated that even diminutive percentages of entrained mica in a sand mixture can increase initial void ratios by as much as

Figure 14 - *Liquefaction boil erupted on April 18, 1990 in fissure formed during Loma Prieta earthquake of October 17, 1989.*

Figure 15 - *Differential settlement associated with April 18, 1990 earthquakes along fissure formed during the Loma Prieta earthquake.*

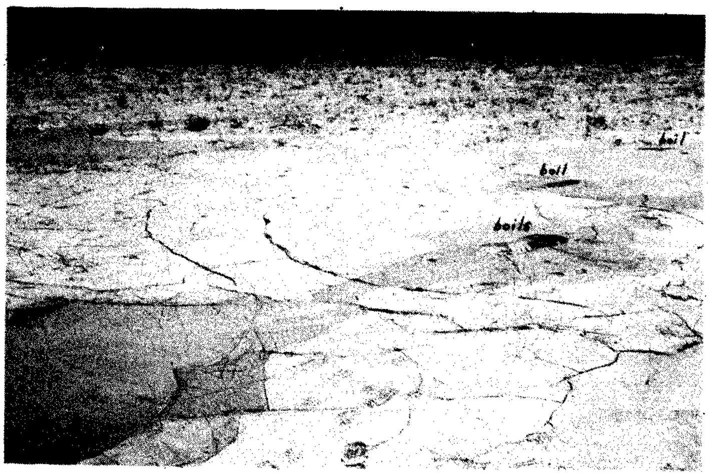

Figure 16 - *Concentric settlement cracks around sand boils suggesting local compaction of liquefied material.*

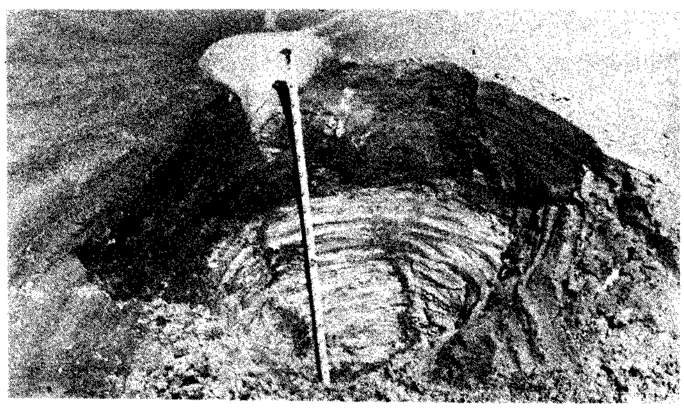

Figure 17 - *Cross-section of liquefaction boil at Soda Lake. Gradations on tape measure blade are in inches.*

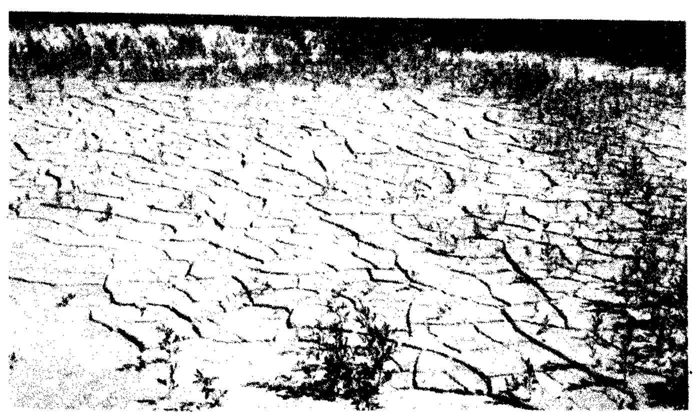

Figure 18 - *The lower (southern) part of Soda Lake, which presumably has a higher water table, showed no evidence for liquefaction. This area is underlain by natural lake deposits, which presumably have a higher natural resistance to liquefaction.*

50%, even though it comprises only 1 to 40% of the mixture. Norris (1975) demonstrated that very angular sands, such as the volcanic sands involved in the 1964 Nigata liquefaction, can be very susceptible to liquefaction due to their naturally loose packing and poor sorting characteristics.

PREDICTABILITY OF LIQUEFACTION

The recently emplaced Soda Lake silts are extremely fine grained for what is normally regarded as liquefiable material. A plot of the average Soda Lake fill grain size on a liquefaction potential plot first proposed by Tsuchida in 1970 (shown in Figure 19) shows the silt mixtures to be in the "potentially liquefiable range." Several factors likely make this material extremely susceptible to liquefaction, even in short-duration shaking. These include:

1. Low initial relative density, due to

   a. hydraulic emplacement

   b. natural grain size sorting during emplacement, yielding fairly narrow size ranges

   c. extreme angularity of the individual grains, thereby causing high void ratios

   d. lack of significant previous dynamic loading

   e. lack of any interstitial cohesive minerals

2. At least some zones within the Soda Lake basin are likely saturated, even when the surface appears dry, because of springs within a naturally closed basin.

Keefer (1984) constructed a chart based on data from several hundred earthquakes showing the distance of liquefaction effects from the source fault rupture zones. According to this chart, a M5.4 earthquake has caused observed liquefaction up to only 6 km from its hypocenter. Soda Lake is about 6 km from the hypocenter.

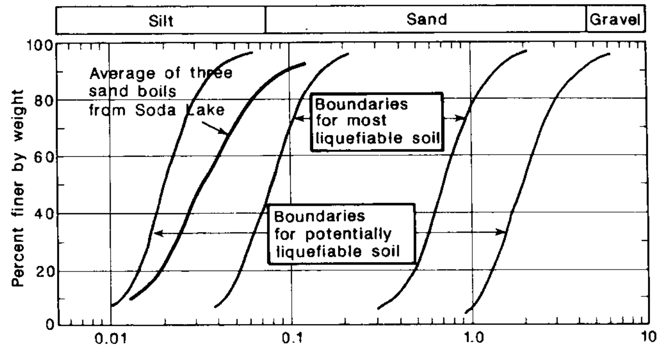

Figure 19 - *Grain size distribution of the average of three samples taken from Soda Lake sand boils plotted on chart showing "most liquefiable" and "potentially liquefiable" soil. Adapted from Tsuchida, 1970, as reprinted in Housner and others, 1985.*

REPEATABILITY OF LIQUEFACTION

Other workers have given considerable thought to the documented susceptibility of a granular deposit to repeated liquefaction because of the intrinsic belief that dynamically-induced consolidation is presumably a "one-way street". By this means, a sand or silt's respective relative density must certainly increase with each episode, thereby possessing less potential for further densification in subsequent seismic events.

A model for repeated liquefaction of a deposit due to partial compaction has been proposed by Finn et al (1970) and was summarized as:

> *A series of small previous shakings either too weak to cause liquefaction or just barely strong enough to cause [initial liquefaction], allows the soil to densify uniformly and increases subsequent resistance to liquefaction. However, a very strong shaking may cause uneven densification, leaving a topmost looser layer with increased susceptibility to liquefaction* (Housner, et al, 1985, p. 58).

The suggestion by Finn, et al (1970), that strong shaking may produce a loose surface layer capable of repeated liquefactions seems to be borne out in comparing the materials affected by the M 7.1 Loma Prieta with the M 5.4 Chittenden swarm, 6 months later. However, the excess pore water driving such failures appears to have been generated at greater depths along pre-existing tensile fissures, apparently caused by widespread macro-settlement (0.2 to 1.5 meters).

CONCLUSIONS

The Chittenden Swarm of earthquakes on April 18, 1990 occurred on the anniversary of the 1906 quake and six months after the Loma Prieta event. The Chittenden swarm caused relatively little landsliding, but did spawn liquefaction and minor settlement cracking at Soda Lake basin. Neither quake caused any known direct surface fault rupture.

The liquefaction at Soda Lake represents a repeated event in the same areas of the basin, but with lower levels and shorter duration of causative shaking. Although the Soda Lake site needs to be studied with conventional standardized testing methods (SPT, CPT, relative density, insitu dry density), surface observations and limited sampling and testing suggests the following preliminary conclusions may be drawn:

(1) The portion of Soda Lake that experienced marked settlement and liquefaction in both earthquakes contains the northern, post-1968 deposits, comprised almost wholly of cohesionless, hydraulically-deposited silt, with 87% of the mixture finer than the #200 sieve size (0.074 mm).

(2) The portion of Soda Lake (the southern 2/3 of the existing basin) previously loaded by nearby earthquakes of large magnitude and duration, did not appear to liquefy or settle appreciably, despite saturation and the presence of standing water. This is also the area where lake sediments likely reach their greatest thickness (Figure 9).

(3) The Soda Lake basin had been subjected to no less than six M 5+ earthquakes within 50 km over the previous 12 years without appreciable effect on loose, recently-deposited silts.

(4) The 0.2 to 1.5 meters of observed settlement of the northern basin sediments during the Loma Prieta quake was likely confined to post-1968 hydraulically-emplaced silts.

(5) The amount of settlement in comparison with observed free surface water after the Loma Prieta event suggest that much of the hydraulic fill silts were either unsaturated or only partially saturated at the time of dynamic consolidation. Much of the expelled free water was observed to percolate back into the alluvium within several days. Some free water decanted to the lower, southern side of the lake which appears to be saturated much of the year. The Soda Lake deposit appears to be strongly stratified with varying levels of entrained moisture.

(6) In both sequences of liquefaction, boils were concentrated along tension fractures that appear to have been associated with 0.2 to 1.5 meters of vertical settlement.

(7) There appears to have been repeated liquefaction of near surface silts, fed by excess pore water and gases welling up along the tensile fractures created 6 months previous. Partially saturated sands and silts underlying the top 0.3 meter cover did not liquefy in the M 5.4 event.

(8) Because of the close timing between events (6 months), many of the large tension fractures had insufficient time to heal and close up. Consequently, it is possible that excess pore pressures were able to concentrate and effect surface outflowage at lower thresholds of shaking and duration then would normally be expected for such a site.

ACKNOWLEDGMENTS

Liquefaction at Soda Lake was first pointed out to California Division of Mine and Geology geologists by Mark Molinari of Dames and Moore, Inc. on October 20, 1989. An earlier paper describing liquefaction at Soda Lake (Wills & Manson, 1990) was reviewed by E. W. Hart and A. G. Barrows of CDMG. Their comments have helped to refine our understanding of the significance of this event. Field reconnaissance, sampling and test pits were accomplished by John Halliday, Jeff Bachhuber and John Woodruff of Rogers/Pacific. Laboratory testing and classification was performed by Fred Chin. Melanie Ham and Kathy Lassalle of Rogers/Pacific kindly typed and edited the manuscript.

REFERENCES

Allen, J.E., 1946, Geology of the San Juan Bautista quadrangle, California: California Division Of Mines Bulletin 133, p. 75, 2 plates, scale 1:62,500.

Bolt, B.A., 1988, Earthquakes, 2nd edition, W.H. Freeman Co., New York, 282 pp.

Bryant, W.A., Smith D. P. and Hart, E.W., 1981, The Sargent, San Andreas, and Calaveras Fault Zones: Evidence for Recency in Watsonville East, Chittenden, and San Felipe Quadrangles, Monterey, San Benito, Santa Clara, and Santa Cruz Counties, California, California Division of Mines and Geology Open File Report 81.7.

CSMIP (1989), "Plots of the Processed Data for the Interim Set of 14 Records from the Santa Cruz Mountains (Loma Prieta), California Earthquake of 17 October 1989," Report No. OSMS 89-08, California Strong Motion Intrumentation Program, Division of Mines and Geology, California Department of Conservation, Sacramento, California, December, 142p.

Dibblee, T.W., Jr., and Brabb, E.E., 1978, Preliminary geologic maps of the Chittenden, Los Gatos, and Watsonville east quadrangles, California: U.S. Geological Survey Open File Report 78-453, 3 sheets, scale 1:24,000.

Ellis, William C., 1952, Elevations on the top of the blue clay zone, Hollister area: U.S. Bureau of Reclamation, unpublished map.

Finn, W.D.L., Bransby, P.L., and Pickering, D.J., 1970, Effects of strain history on liquefaction of sands: Journal of the Soil Mechanics and Foundations Division, American Society of Civil Engineers, 96 (SM6), p. 1917-1934.

Gilboy, G., 1933, Hydraulic-Fill Dams, Proc. Int. Comm. on Large Dams, World Power Conf., Stockholm.

Hart, E.W., Bryant, W.A., Wills, C.J., and Treiman, J.A., 1990, The search for surface faulting and significance of ridgetop fissures, *in* S. McNutt and R.H. Sydnor, editors, The Loma Prieta earthquake of October 17, 1989: California Department of Conservation, Division of Mines and Geology Special Publication 104, in press.

Higgins, C.T., 1989, Arthur R. Wilson quarry - where nature gives man a break: California Geology, v. 42, no. 11, p. 256-259.

Housner, G.W. and the Committee on Earthquake Engineering, National Research Council, 1985, Liquefaction of soils during earthquakes: National Academy Press, Washington, D.C., 240 p.

Huber, W.C., 1929, The San Francisco Earthquakes of 1865 and 1868, Bull. Seismological Soc. Am., v.20, n.4, pp. 261-272.

Jenkins, O.P., 1973, Pleistocene Lake San Benito: California Geology, v. 26, no. 7, p. 151-163.

Jordan, D.S., 1907 (editor), The California Earthquake of 1906, A.M. Robertson publication, San Francisco, 371 pp.

Keefer, D.K., 1984, Landslides caused by earthquakes: Geological Society of America Bulletin, v. 95, p. 406-421.

Lawson, A.C., and others, 1908, the California earthquake of April 18, 1906; Report of the State Earthquake Investigation Commission: Carnegie Institute of Washington Publication 87, 2 volumes, 452 p.

Leopold, L. B., Wolman, M. G. and Miller, J. P., 1964, Fluvial Processes in Geomorphology: W. H. Freeman and Co., San Francisco, CA, 522 p.

Louderback, G.D., 1947, Central California earthquakes of the 1830's: Bulletin of the Seismological Society of America, v. 37, p. 33-74.

Norris, G., 1975, The Effect of Particle Size and the Natural Variation in Particle Shape and Surface Roughness on the Stress-Strain and Strength Behavior of Uniform Quartz Sands, Ph.D. Thesis, University of California, Berkeley.

Rogers, J. David, 1982, The Genesis, Properties and Significance of Fracturing in Colorado Plateau Sandstones, Unpublished Ph.D. dissertation, Geological Engineering, University of California, Berkeley, 706 pages.

Seed, H.B, and Makdisi, F.I., 1977, A Simplified Procedure for Estimating Earthquake-Induced Deformations in Dams and Embankments, Rept. No. UCB/EERC-77/19, University of California, Berkeley.

Tsuchida, H., 1970, Prediction and countermeasure against the liquefaction in sand deposits: Abstract of the Seminar in the Port and Harbor Research Institute, p. 3.1-3.33 (in Japanese).

Wills, C.J., Manson, M.W., 1990, Liquefaction at Soda Lake: Effects of the Chittenden Earthquake Swarm of April 18, 1990, Santa Cruz County, California: California Geology, v. 43, no. 10, p. 225-232.

Youd, T.L, and Hoose, S.N., 1978, Historic ground failures in northern California triggered by earthquakes: U.S. Geological Survey Professional Paper 993, 177 p.